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Correlation of VERES Predictions for Multihull Ship Motions

by

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A correlation effort was completed to determine if the VEssel RESponse (VERES) program was suitable for predicting the motions of high-speed multi-hull vessels. Head and bow wave heave and pitch responses correlated reasonably well with available model test result, with VERES tending to over-predict response magnitudes as speed is increased. A limited study of the use of fins for motion control demonstrated the possibility of a large reduction in motion at high speed, using a set of four fins.

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Contents

Figures

Figures (cont)

Tables

Page

Abstract

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Administrative Information

The Seakeeping Division (Code 5500) of the Hydromechanics Department at the Naval Surface Warfare Center, Carderock Division (NSWCCD), performed the work described in this report. The U.S. Army-sponsored Theater Support Vessel and the USN Rapid Strategic Lift Ship Programs funded the work under Job Order Numbers 03-1-2300-906-42 and 05-1-2123-404-52 respectively.

Introduction

As a result of increased interest in high-speed vessels, there is a Navy need to predict the seakeeping performance of such vessels, including motions, loads and ride control. Conventional ship motion theory, as implemented in the Navy's standard ship motion program SMP [1]*, is limited to monohulls and moderate speeds. High-speed ship designs are likely to involve multi-hulls, either catamarans or trimarans. Thus, prediction of motions must include the capability for handling two or three hulls, and must be capable of making accurate predictions at high speed (i.e., high Froude number, or Fn). One available method is a computer program named VERES, which is part of the SHIPX design package available from Marintek [2]. VERES is a strip-theory program, in which hull geometry is represented by coordinate points defined at a number of stations along the length of the hull. This program includes the capability for predicting multihull motions and loads, includes a high-speed strip theory [3] as well as conventional strip theory [4], and can be used to examine the effect of fixed or controllable fins on motions.

The output from VERES can include statistics of responses in random waves. However, these predicted statistics are calculated using standard spectral techniques in which the required basic response characteristics are defined by their transfer functions or Response Amplitude Operators (RAOs). Therefore, the accuracy of the basic physics incorporated in VERES calculations can be evaluated by correlating the RAOs to available experimental data. This report evaluates the heave and pitch (and, in one case, roll) RAOs predicted by VERES, comparing these predictions with available model test data for several high-speed, multihull ships.

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* References, in brackets, can be found on page 25.

Hull Forms

Four hull forms were selected for the correlation effort: two catamarans and two trimarans. These hull forms have published experimental results for heave and pitch motions in head waves [5-8]. Test conditions and principal hull characteristics are shown in Tables 1 and 2.

Case 1 [5] is a mathematically defined hull form, in which all station cross-sections are Lewis forms and the demihulls are symmetric both transversely and longitudinally - the bow and stern sections are identical (Fig. 1). Model tests were done at Fn = 0.15 and 0.30.

Case 2 is a catamaran designed at Delft Technical University. This case does not have longitudinal symmetry: the forward sections are V-shaped, while the aft sections are faired into a transom that has the full beam of the hull at the deck (Fig. 2). This transom has zero immersion at rest (Fn = 0.0). The model was tested at both Delft [6] and MARIN [7], at speeds of Fn = 0.30 and higher. In tests at Delft the model was towed with a heave staff (surge restrained), while the tests at MARIN were done with a free-running, self-propelled model (propulsion was with waterjets). A comparison of these results allows a rough estimate of the effect of test methodology as well as an assessment of VERES. The test program at Delft included forced oscillation tests to determine added mass and damping coefficients, and the effect of dynamic sinkage and trim was also investigated.

Case 3 is a trimaran tested at the U. S. Naval Academy Hydromechanics Laboratory. [8]. The Naval Academy test program in calm water (resistance tests) included three transverse and three longitudinal locations of the side hulls relative to the center hull, and was done at two drafts, for a total of 18 conditions. The seakeeping tests were done for Fn = 0.15 and 0.30 at only one draft and one transverse offset, but with the hulls at two longitudinal locations (Fig. 3). (The "forward" location still had the center of the side hulls after of midship relative to the center hull).

Case 4 is a trimaran hull recently tested at NSWCCD[†]. The body plan is shown in Fig. 4. Seakeeping tests were done at Fn = 0.30 and higher.

Correlation with VERES

Case 1 (Lewis Form Catamaran)

The magnitudes of the heave and pitch transfer functions from the model test and predictions from VERES are shown in Figs. 5 and 6. The horizontal scale in these Figures is the ratio of wave length (λ) to ship length (L). Heave is made non-dimensional by wave amplitude, pitch by wave slope kA, where k is the wave number ($k = 2\pi / \lambda$) and A is the wave amplitude. Initially, the VERES calculations were made with 24 stations and ordinary strip theory, which were then increased to 41 stations. There was little difference attributable to the increased number of stations, but, to be conservative, 41 stations were used for all further VERES calculations (including Cases 2, 3 and 4 below). The high-speed theory correlated somewhat better to the model test data at Fn=0.30, while the ordinary theory was better at Fn=0.15. This is consistent with the recommendations in the VERES manual. The high-speed theory is able to predict the

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[†] High Speed Sealift (HSS) Model test, NSWCCD report in preparation.

inflection in the pitch RAO at Fn = 0.30 and $\lambda / L \approx 1.8 - 2.0$. There is also a menu option in the version of VERES used here (v.3.23.7) to use a strip theory designated "High Speed Cat w/ Hull Int.", although this is not documented in the VERES manual. The results of this option are also shown in Fig. 5. The correlation for this option is, in general, poor, resulting in a serious over prediction at Fn=0.15 (not surprising since it is intended for high speed), and a serious underprediction at Fn=0.30. Since this option is an undocumented "feature" of VERES, it was not used in further comparisons. For all subsequent comparisons to VERES, the high-speed theory (without hull interactions) has been used, except for Fn<0.30. Figure 6 shows the comparison on this basis, for Case 1. On this basis of comparison, the correlation to the model test data is reasonable, although the VERES predictions do not capture the details in shape of the data for Fn=0.15 around $\lambda / L \approx 1.0 - 1.5$. This may be due to interaction between the two hulls, which is expected to be more obvious at lower speed.

Case 2 (Delft Catamaran Hull 372)

The correlation of VERES predictions to the Delft and MARIN model tests is shown in Figs. 7-15. The VERES high-speed strip theory option was used for the predictions, with input data at 41 stations. The input offsets in Ref. 5 was tabulated for uneven station spacing; these were interpolated to provide 41 stations with even spacing for use in VERES computations. Since model tests at MARIN included several oblique (bow) wave headings, VERES predictions for these headings were included in the correlation.

Head Waves

The heave and pitch motions in head waves are shown in Fig. 7. The differences between results from the two test tanks (Delft and MARIN) are generally small, and may be at least partially explained by the different test methods: The model was towed at Delft with surge restrained, while at MARIN it was free-running, self-propelled by waterjets. The correlation to VERES is good at Fn=0.30, but there is increasing discrepancy at higher speeds, especially for pitch. VERES tends to overpredict the motions as Froude number is increased, particularly at resonance. It is possible that the damping of the model includes significant viscous or lift components that are not included in the potential flow calculations of VERES (see also the discussion of dynamic trim below). Note that the lowest Froude number in this case is the same as the highest Froude number for Case 1; comparisons for Case 2 are made only to the high speed theory in VERES.

There was an extensive test program at Delft that included forced oscillation tests to determine added mass and damping coefficients A_{ij}, B_{ij}. Wave excitation force and moment and sinkage and trim were also measured, and it was recognized that the restoring coefficients C_{ij} at high speed would not necessarily be the same as at rest (where they are simply properties of the static waterplane), because of sinkage, trim, dynamic lift and wave profile. Some of these effects are investigated and shown in Figs. 8 and 9. In Fig. 8, the VERES calculations have been redone using the sinkage and trim measured in the Delft experiments (VERES has the option to accept specified sinkage and trim which changes the interpolated station offsets used in the calculations). As shown in Fig. 8, this effect accounts for approximately half the discrepancy between the model test data and the original VERES calculations (done without sinkage and trim). Of course, this requires knowledge of the sinkage and trim. A further set of calculations is

shown in Fig. 9, in which the experimentally measured values of A_{ij}, B_{ij}, C_{ij} and F_j were used in the equations of motion to calculate the heave and pitch. Clearly, these data do not improve the correlation. The large peak in heave at $\lambda / L \approx 1.6$ corresponds to the heave natural frequency. It is possible that the heave motion actually has more damping at resonance than was evident in the forced oscillation experiments.

Bow Waves

The model was tested (at MARIN only) for headings of 15 and 45 degrees off the bow (designated as 195 and 225 deg, since head waves are defined as a heading of 180 deg). The tests were conducted at Fn = 0.30, 0.60 and 0.75 (but not 0.45). The correlation has been done only for the magnitude of heave, roll and pitch. MARIN test data is available for surge, sway and yaw. However, these motions in oblique waves are expected to depend on the steering of the model, i.e. the type of autopilot used. The steering is not documented in Ref. 5, so no attempt was made to correlate these data to VERES.

The heave, roll and pitch motions at 195 deg heading are shown in Figs 10-12. The results at this heading are generally consistent with what was found in head waves: The correlation at Fn = 0.30 is good, but VERES tends to over-predict heave and pitch as Froude number is increased, especially for pitch. The roll magnitude is quite small, but the correlation of roll RAOs between VERES and the MARIN test data seems satisfactory.

The heave, roll and pitch motions at 225 deg heading are shown in Figs 13-15. Again, the pitch is over-predicted at the higher speeds. The heave correlation is satisfactory. The roll magnitude is larger at this heading, as expected, and the correlation between VERES and the MARIN data is good, considering that there appears to be a considerable scatter in the test data.

It is interesting to note that the roll magnitude shows only a modest peak at this heading, indicating that the model is well-damped in roll. That is, the roll damping is a relatively large percentage of critical, compared to typical monohulls. Although it can be dangerous to generalize, this property may be a common property of catamarans, as long as the beam/draft ratio of the individual demihulls , and the spacing between the hulls, is not too small. The reason for this may be that the roll damping comes primarily from radiated waves from the individual demihulls heaving (out of phase with each other, i.e. one demihull going down while the other is going up). In this case, the roll damping would be expected to be approximately $B_{44} \approx y^2 B_{33}$, where y is the distance from the centerline of the catamaran to the centerline of a demihull, B_{44} is the roll damping coefficient and B_{33} is the heave damping coefficient. A similar relationship would be expected between roll and heave added mass. Examination of the details of the VERES confirms this.

For example, for the 372 model at Fn = 0.75, the estimated roll natural frequency is $\omega_n \approx 7.7$ rad/sec, and this frequency of encounter at 45 deg off the bow corresponds to $\lambda / L \approx 1.8$, which agrees with the (modest) roll peak in Fig. 14. At this frequency, the VERES calculations may be summarized as follows (all the following numbers are from potential flow only, and A_{33}, A_{44}, B_{33}, B_{44} are the heave and roll added mass, and the heave and roll radiation damping respectively):

A_{33}	A_{44}	$(y^2 A_{33})$	B_{33}	B_{44}	$(y^2 B_{33})$
57.1	7.18	(6.99)	358	44.6	(43.9)

The numbers in parentheses are calculated with the approximate formula shown above, and are within a few percent of the actual values calculated by VERES. VERES also includes an equivalent linear roll damping due to viscous effects. This has a value of 16.2 (kg*m^2/s) which when added to the wave damping gives a total of 60.8. Thus, the wave damping is about ¾ of the total roll damping calculated by VERES. Note that the VERES viscous damping for multihulls is not documented in the manual. Also, these calculations have been made with a nominal wave amplitude (1 m) which is obviously larger than what was used in the model tests (typically ~ 2 cm). If the VERES calculations were redone with a smaller wave amplitude, or with the viscous effects removed completely, the roll damping would be about ¾ as large, so that the peak roll motion would be about 4/3 larger. This would still leave the correlation no worse than for a typical monohull correlation

Case 3 (USNA Trimaran)

The correlation to VERES for this case is shown in Fig. 16. In general, the correlation for pitch is very good for both speeds, as is the heave correlation at the lower Froude number. In the VERES calculations, ordinary strip theory was used for Fn = 0.15, while the high-speed strip theory was used for Fn = 0.30. The heave correlation at the higher Froude number is not as good near $\lambda / L = 1$, although the qualitative shape of the curve matches the data. It should be noted that a Froude number of 0.30 lies in the "gray area" where the VERES manual indicates that either ordinary or high-speed may be used. The longitudinal location of the side hulls has little effect on pitch, while the effect on heave is qualitatively the same for both the model test and the VERES calculations.

Case 4 (HSS Trimaran)

This model was tested at NSWCCD at speeds of 35, 45, 55 and 65 knots for a 300 m hull (Fn = 0.32, 0.42, 0.51, 0.60) in waves at various headings. However, regular wave RAOs were only available for one condition, head waves at Fn = 0.51. The results are shown in Fig. 17, and show excellent correlation for both heave and pitch magnitude. VERES predictions for other speeds are shown in Fig. 18.

Motion Control with Fins

VERES has the capability to predict the effect of fins on the motions. Active fins are often used to reduce the amplitude of motions, especially when the motions are lightly damped and the forward speed is high. As an initial study of motion control using VERES, the Delft catamaran 372 was fitted with two pairs of active fins, one pair forward and one aft (Fig. 19). The fin motion (δ) was driven by heave rate with a gain of 0.4 rad/(m/s). The motivation for this was the observation that the large heave peak (in the uncontrolled case) at Fn = 0.75 was a lightly damped heave resonance. The way to reduce the amplitude of a system at resonance is to increase the damping by any means available. The gain was chosen to be realistic, not so large as to require excessive angles on the fins. The results are shown in Fig. 20. The peak of the heave RAO is reduced about 70%. The large peak in the pitch RAO is believed to be caused by heave coupling, rather than direct pitch resonance (this is based on an estimate of the uncoupled natural frequencies, which shows that $\lambda / L \approx 1.9$ at Fn = 0.75 corresponds to the heave natural frequency, not the pitch natural frequency). This is confirmed by the reduction of the pitch peak

by about 50% when heave is controlled by fins. The fin RAO is also shown and made non-dimensional by wave slope just as is done with pitch.

To get some feeling about how big the fin motion is for this case, notice that the fin RAO is about 3 for $\lambda / L = 2.0$. If one considers a wave of moderate steepness, $2A/\lambda = 1/50$, one finds $KA = 2\pi/100$, so with an RAO of 3, the fin angle is $\delta = 6\pi/100 = 0.188 \text{ rad} = 10.8\deg$. If the wave were twice as steep, the fin angle would double to 21.6 deg. This is considered a realistic fin angle range.

This is merely a preliminary study to investigate feasibility of improving motion resonances by active fin control. Fin sizes and locations, as well as controller gain, are initial estimates, subject to further refinement. Further improvement in pitch might be obtained by driving the forward/aft fin pairs differentially, controlled by pitch and/or pitch rate. These VERES calculations are not validated by any model tests, and in fact the VERES correlation to the uncontrolled (no fin) pitch data at Fn = 0.75 was not particularly good (see Figs. 7-15). Also, the effect of the fins should be checked for all headings, and for lower speed. The fins are expected to be less effective at lower speed, but the need for them may also be less.

Conclusions

A comparison of VERES predictions to available model test data for several high-speed catamarans and trimarans has shown generally reasonable correlation for heave and pitch RAOs. The correlation is somewhat better for trimarans than for catamarans. Where discrepancies exist, several possible causes have been identified. High-speed hull forms are inherently slender, which means the damping based on potential flow (radiated waves) is relatively low compared to conventional hull forms. High forward speed in head or bow waves may result in encounter frequencies that match the resonant frequency of heave or pitch. For catamarans, VERES generally predicts a peak (resonant) response that is higher than seen in model test results, especially for pitch. The prediction of damping in VERES is based on linear potential flow (damping by radiated waves), except for roll in which a viscous damping component is predicted empirically. The actual heave and pitch damping on the models may include significant viscous or lift effects. Furthermore, the sinkage, trim and wave profile at high speed made significantly alter the underwater geometry. Calculations using the experimentally measured sinkage and trim for one case, showed improved correlation. However, a motion calculation using measured dynamic coefficients did not show improvement.

For trimarans, the correlation was very good for both heave and pitch, although VERES overpredicted the heave RAO in one case (again indicating an underprediction of damping). This may be a result of a fundamental difference in geometry for trimarans versus catamarans. Catamarans have two identical (or at least mirror-image about ship centerline) hulls, of equal length. There may be considerable hydrodynamic interaction between the hulls. On the other hand, trimaran configurations typically consist of a large slender hull on centerline, with two much smaller outrigger hulls to port and starboard. The loads on these outrigger hulls, and the loads due to interaction with the centerline hull, may have a relatively minor effect on the overall motions of the total configuration.

Motions of high-speed multi-hull vessels are typically lightly damped. This can cause unacceptably large amplitudes of response at resonant frequencies. However, the high speed also affords an opportunity to reduce using active control surfaces. A preliminary study of catamaran

motion control using VERES shows the potential for significant motion reduction using active fins. This study was done without any comparison to experimental data, indicating the need for future model tests for correlation to VERES predictions.

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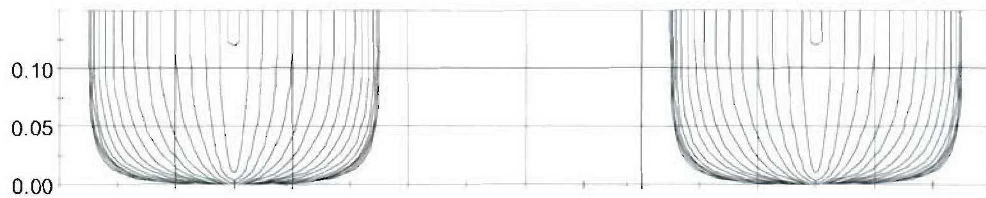


Figure 1. VERES Plot of Lewis Form Catamaran Body Plan

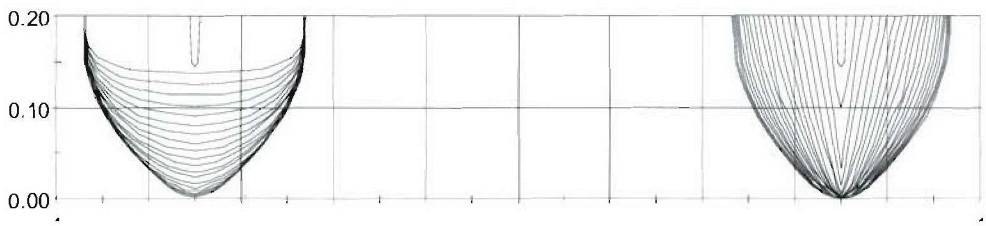
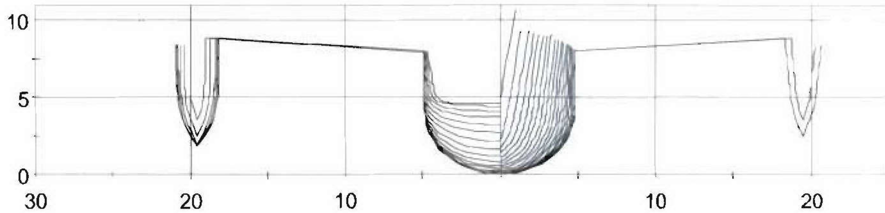
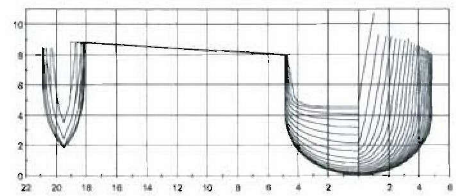


Figure 2. VERES Plot of Delft Catamaran No. 372 Body Plan



a. Side Hull Fwd



b. Side Hull Aft

Figure 3. VERES Plot of USNA Trimaran Body Plan

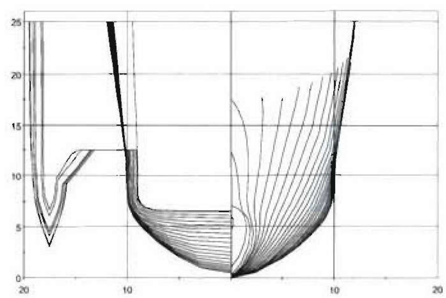


Figure 4. VERES Plot of HSS Trimaran Body Plan

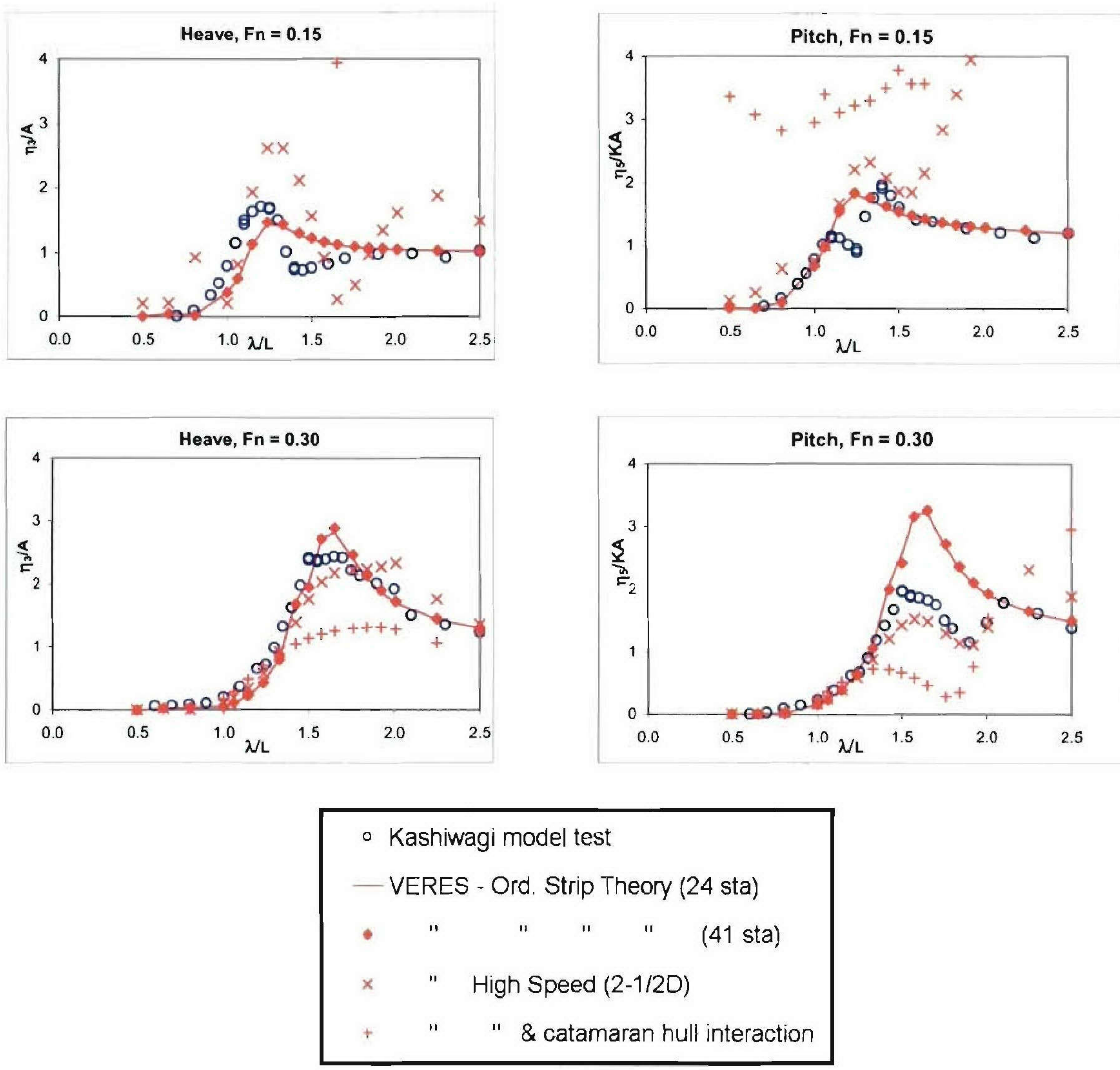


Figure 5. Lewis Form Catamaran – Comparison to VERES, Various Options

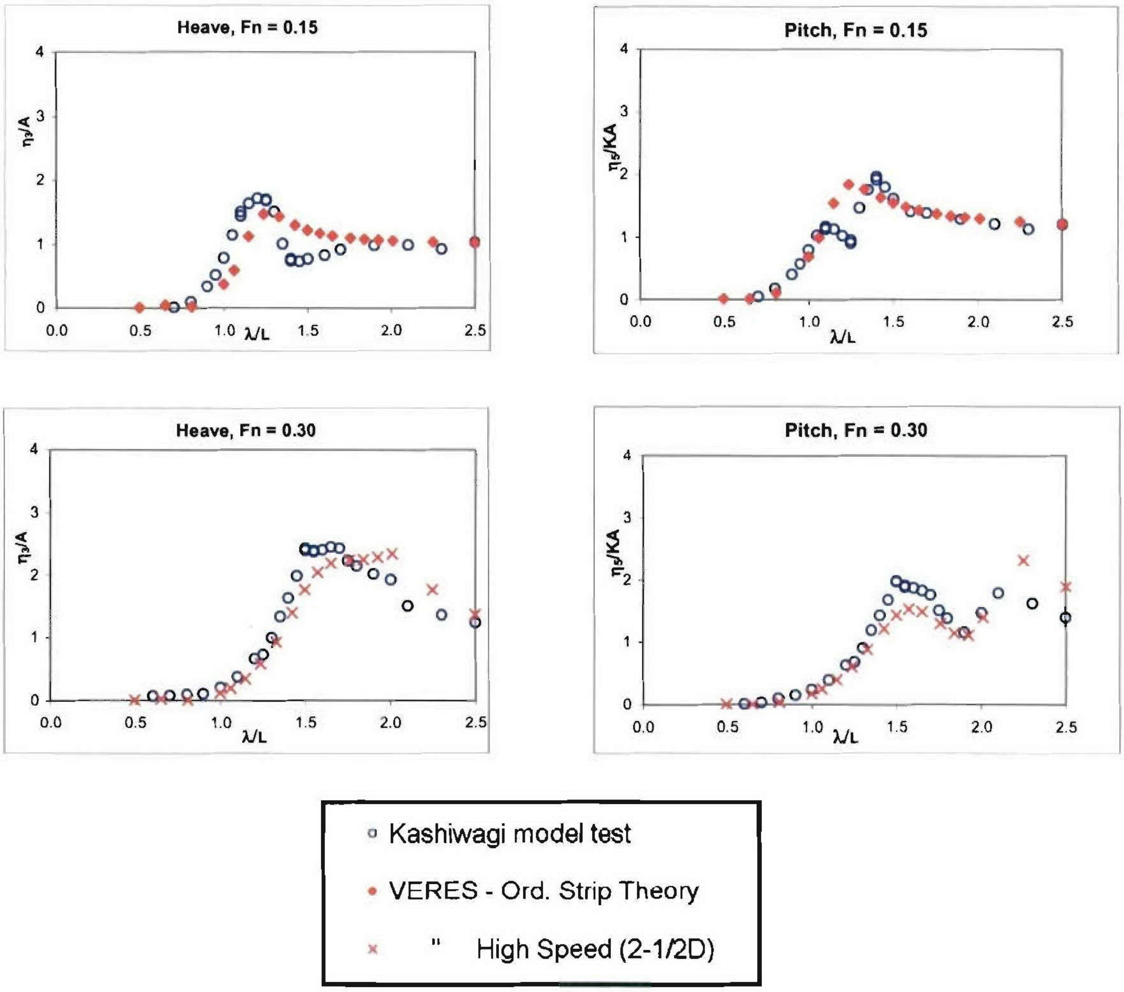


Figure 6. Lewis Form Catamaran

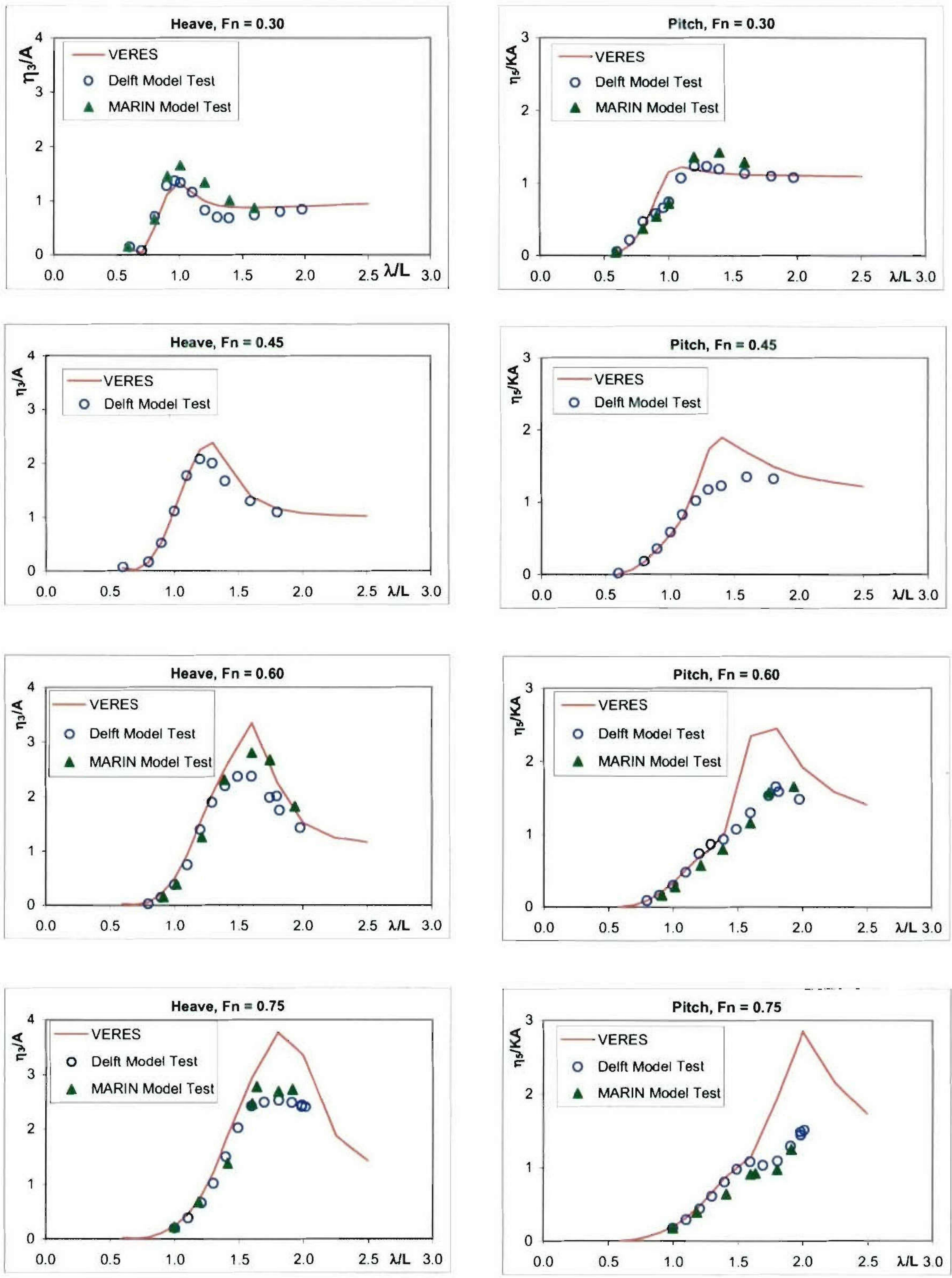
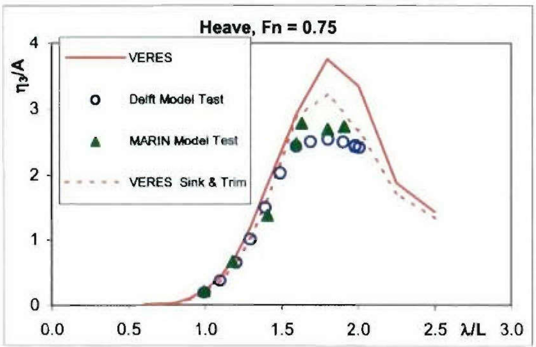


Figure 7. Delft Catamaran No. 372, Head Waves



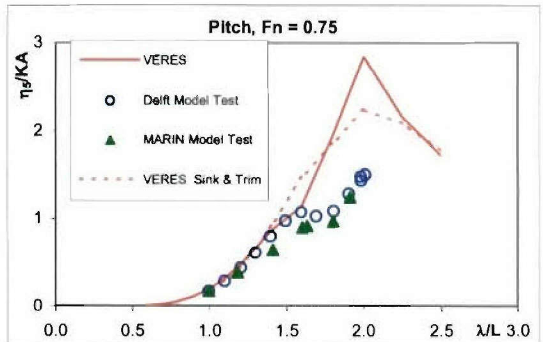
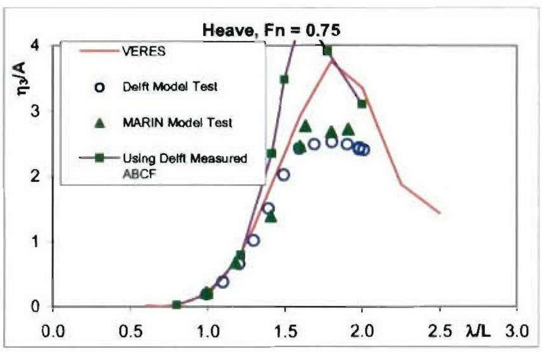


Figure 8. Catamaran 372 at Froude Number = 0.75, with Measured Sinkage and Trim



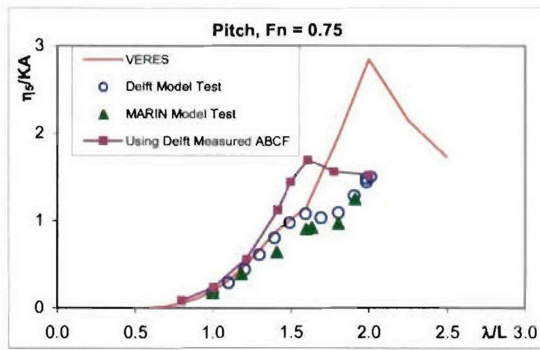
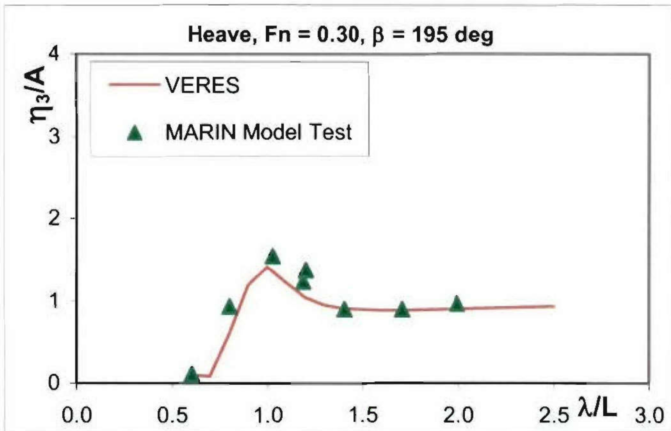
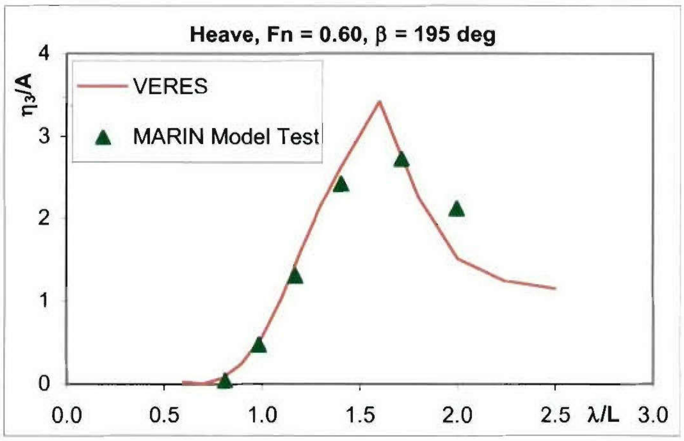


Figure 9. Catamaran 372 at Froude Number = 0.75, with Measured Hydrodynamic Coefficients





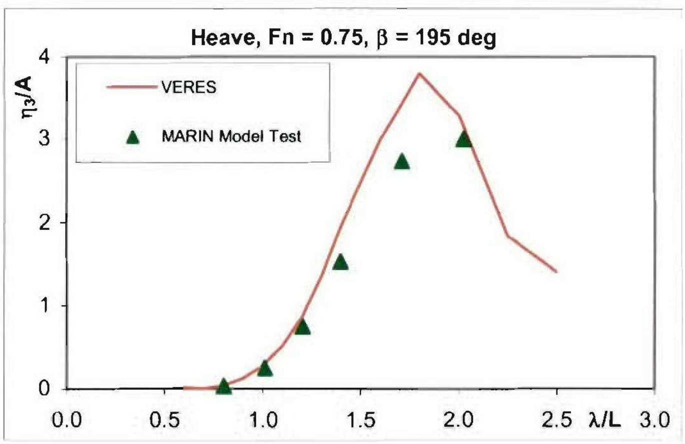
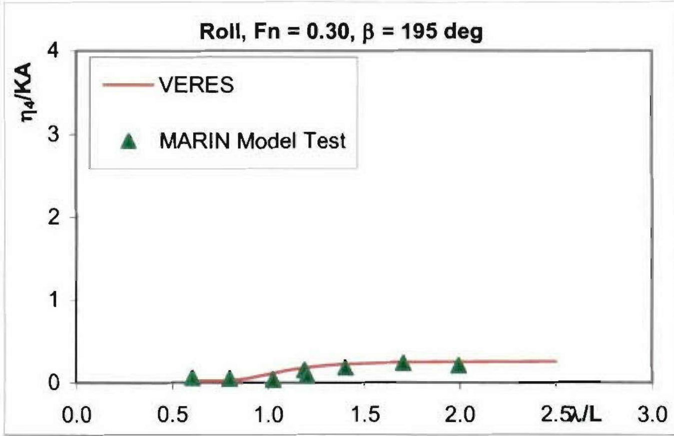
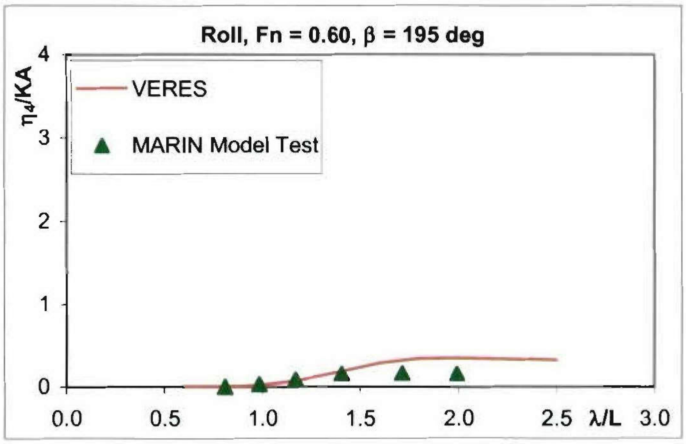


Figure 10. Oblique Wave Heave RAO Correlation, Catamaran 372, 195 Deg Heading





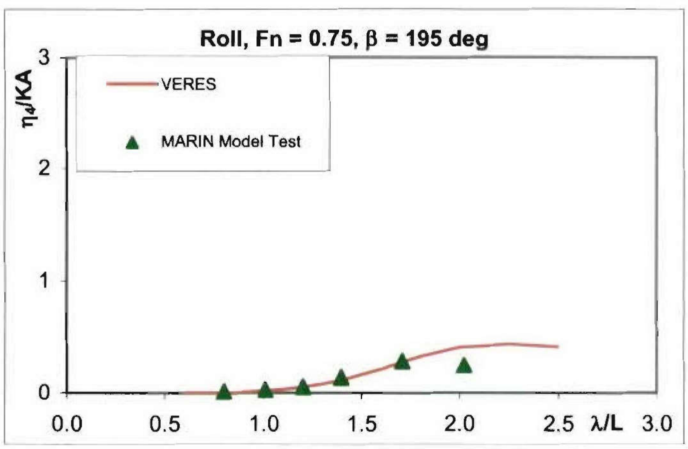


Figure 11. Oblique Wave Roll RAO Correlation, Catamaran 372, 195 Deg Heading

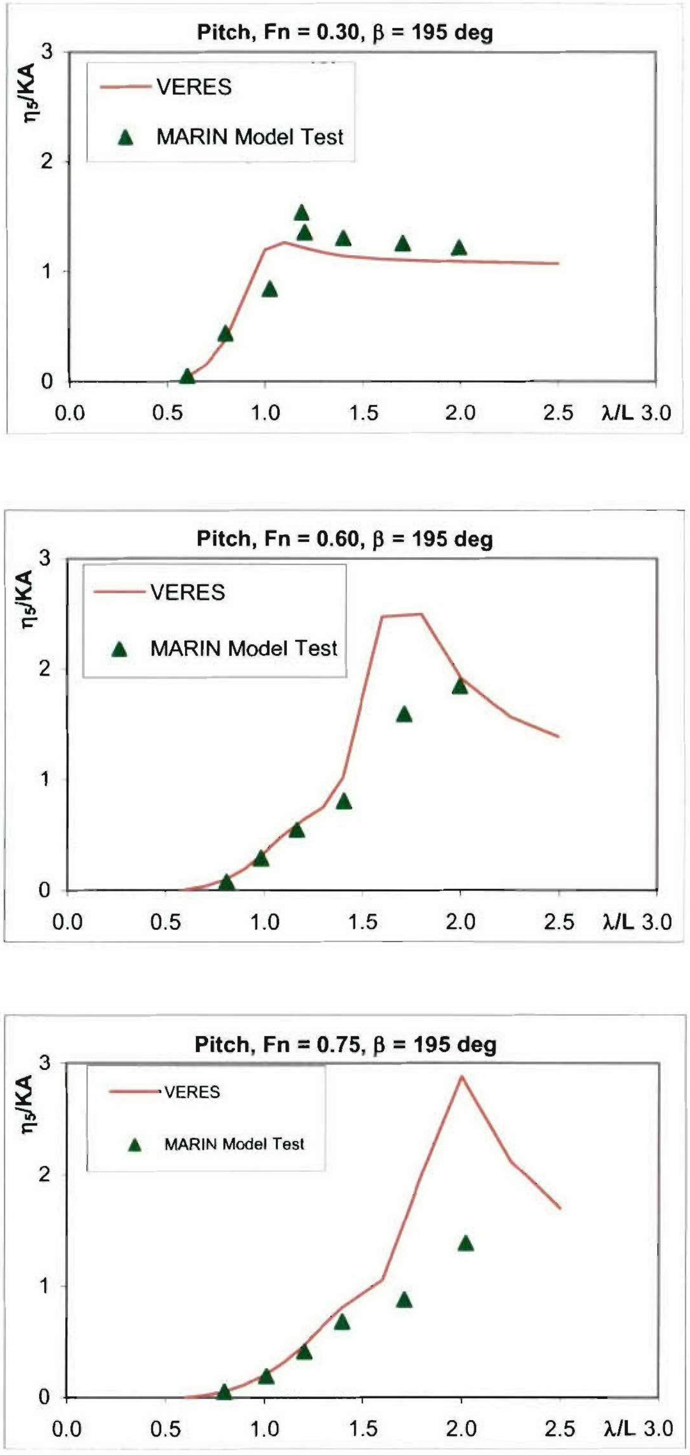
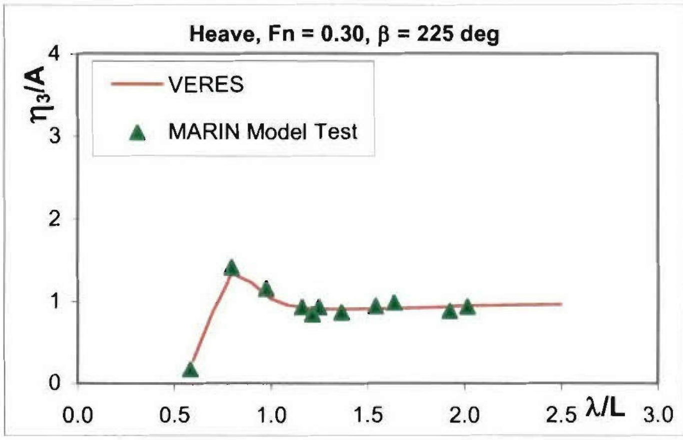
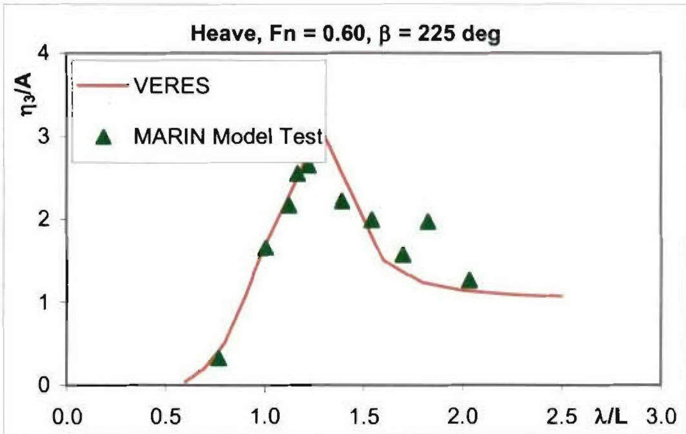


Figure 12. Oblique Wave Pitch RAO Correlation, Catamaran 372, 195 Deg Heading





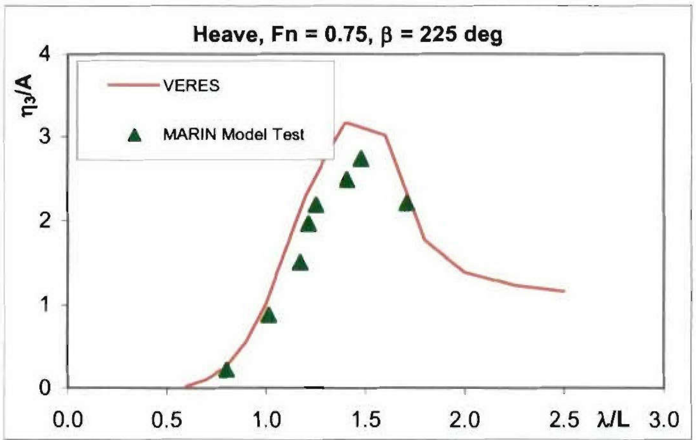


Figure 13. Oblique Wave Heave RAO Correlation, Catamaran 372, 225 Deg Heading

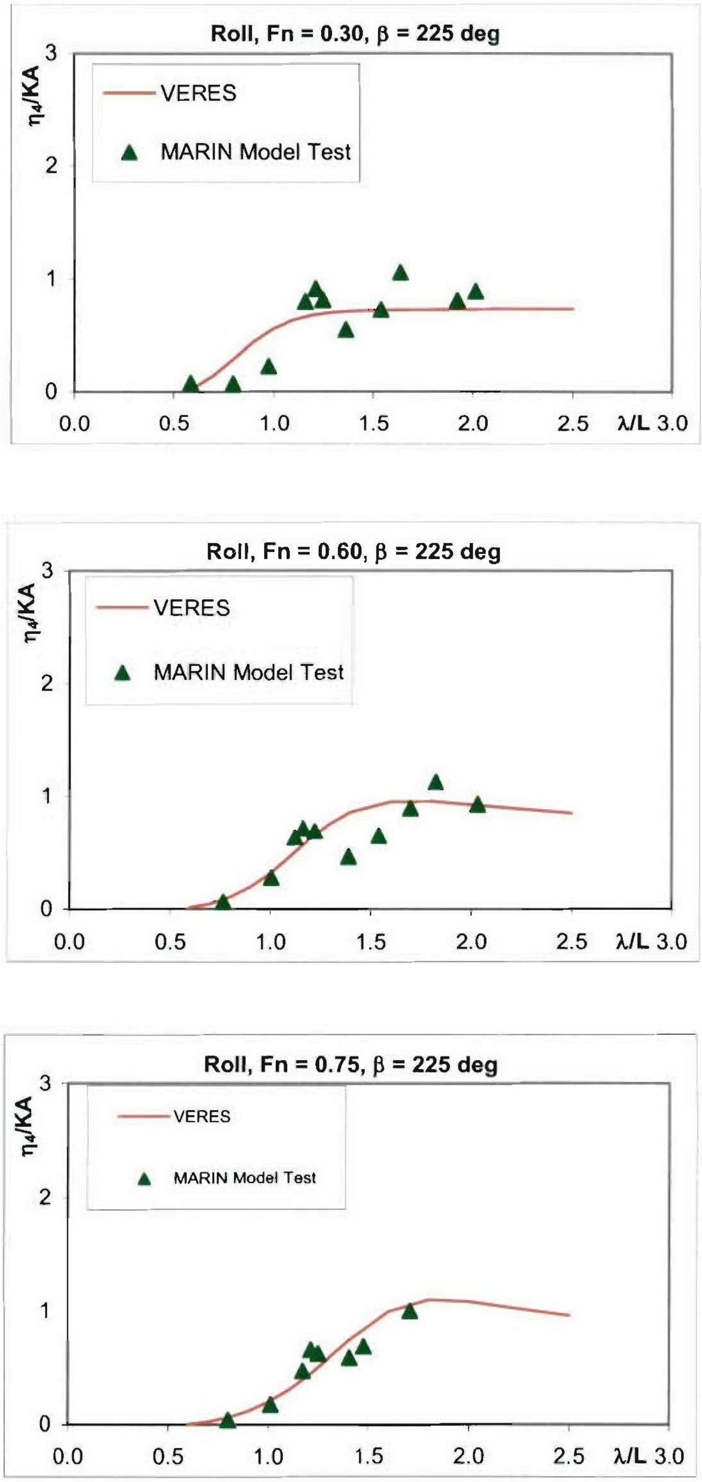
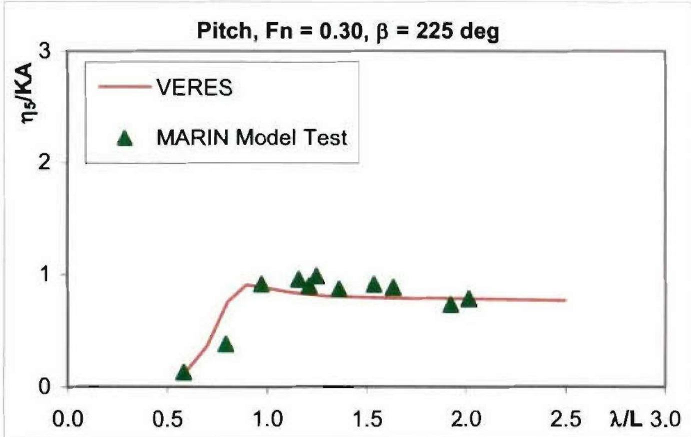
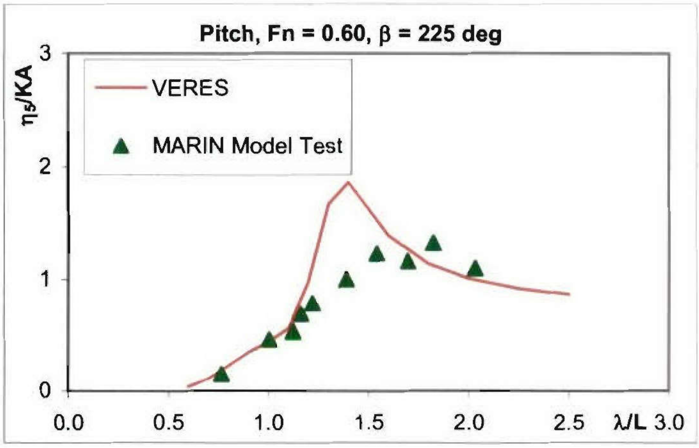


Figure 14. Oblique Wave Roll RAO Correlation, Catamaran 372, 225 Deg Heading





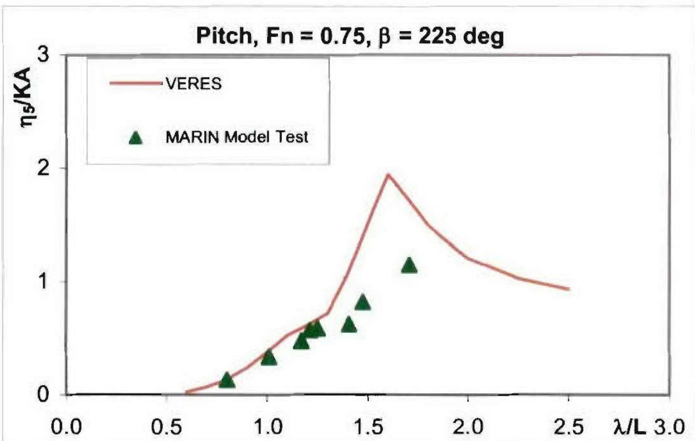
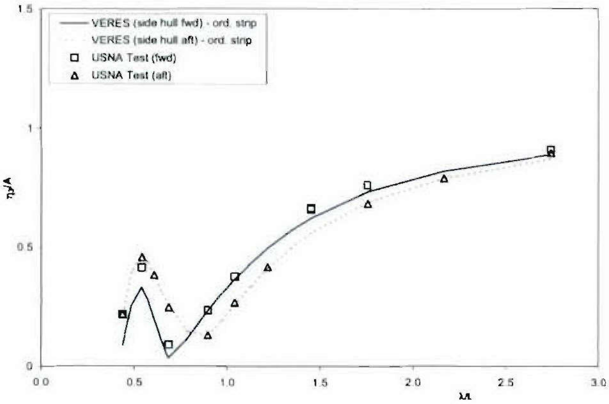
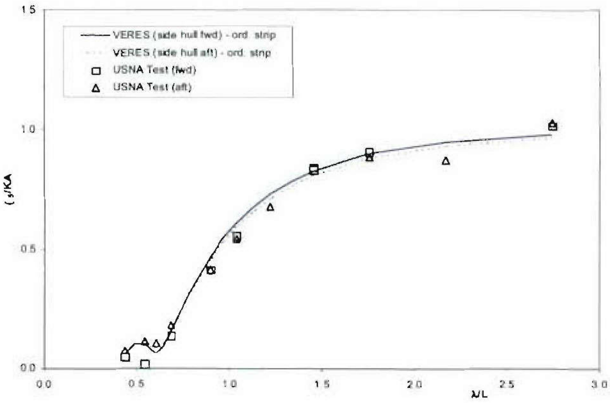


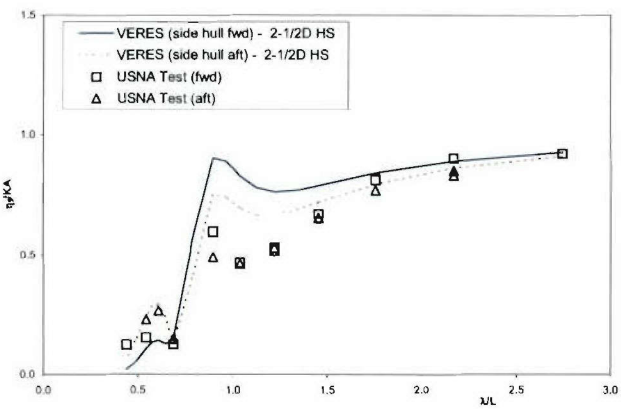
Figure 15. Oblique Wave Pitch RAO Correlation, Catamaran 372, 225 Deg Heading



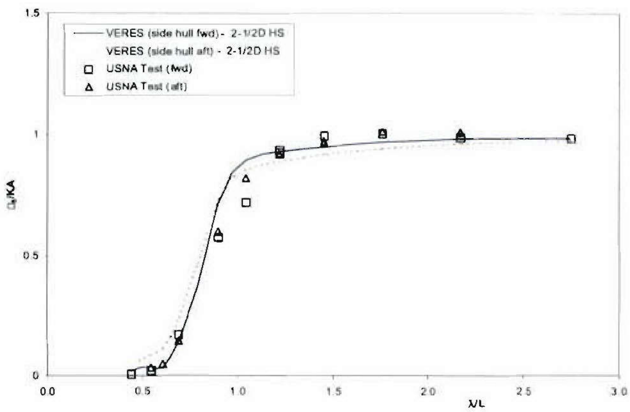
a). Heave, Fn = 0.15



b). Pitch, Fn = 0.15

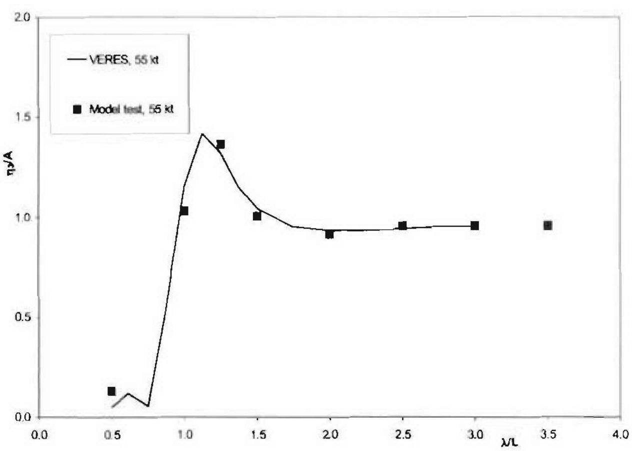


a). Heave, Fn = 0.30

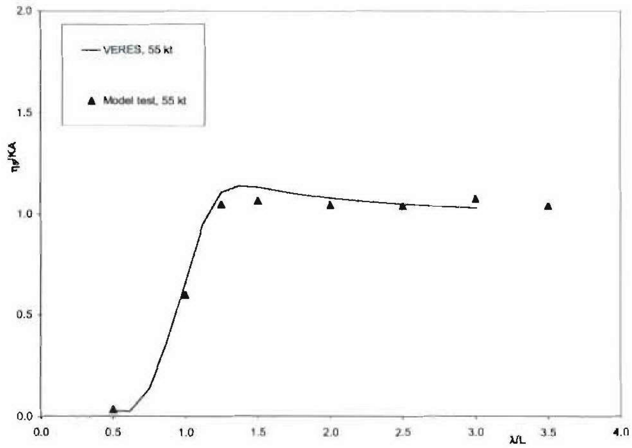


b). Pitch, Fn = 0.30

Figure 16. USNA Trimaran

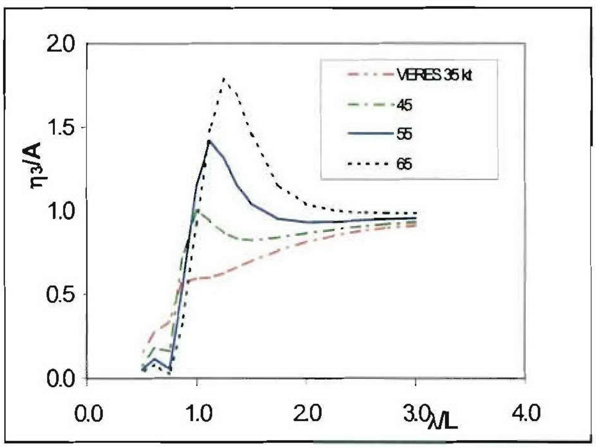


a) Heave

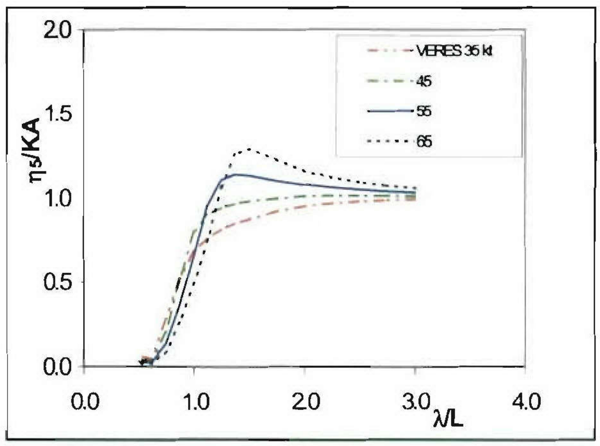


b) Pitch

Figure 17. HSS Trimaran at V = 55 kts (Fn = 0.51)



a) Heave



b) Pitch

Figure 18. HSS Trimaran, VERES Predictions

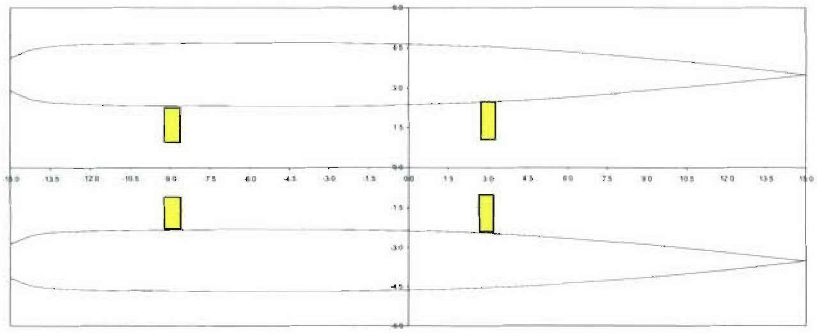


Figure 19. Fin Geometry for Motion Control

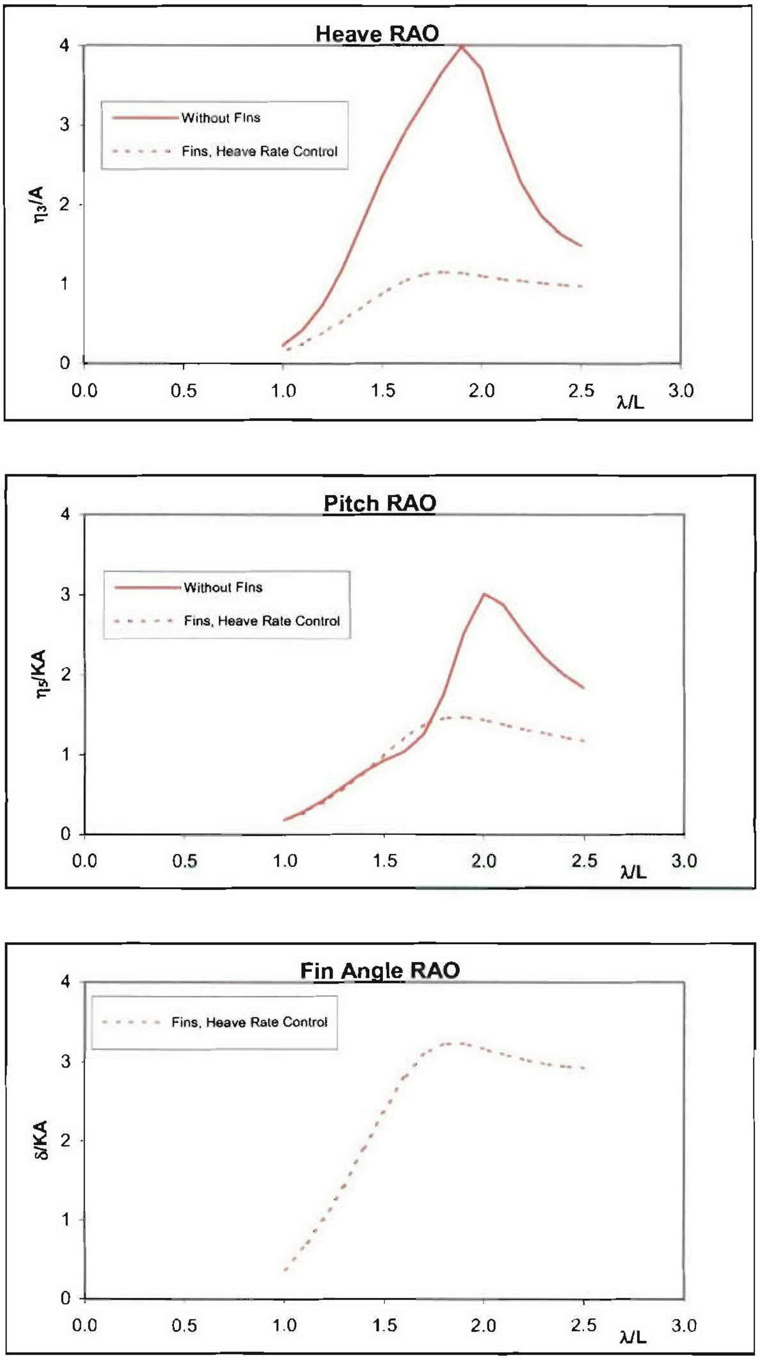


Figure 20. Predicted Effect of Fins on heave and Pitch

Table 1. Multihull Cases Used for Correlation

Case	Hull Type	Source	Ref.	Length(m)	Froude Numbers
1	Catamaran	Japan	4	1.50	.15, .30
2	"	Delft	5,6	3.00	.30, .45, .60, .75
3	Trimaran	USNA	7	3.56	.145, .29
4	"	NSWCCD	8	6.96	.32, .42, .51, .60

Table 2. Principal Characteristics

Case	1	2	3	4
$L/B^{(1)}$	6.00	12.50	13.12	15.00
$B/T^{(2)}$	2.00	1.60	2.13	2.35
D/B	2.00	2.92	2.00	0.88
R_Y/L	0.225	0.261	0.250	0.282

Notes:

1 - B taken as beam of individual demihull (catamaran) or center hull (trimaran)

2 - D is spacing between centerlines of hulls and/or side hulls

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